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THE PINPOINT SYSTEM DEFINITION STUDY

BAE Systems

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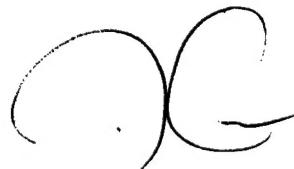
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13. ABSTRACT (Maximum 200 words)

The purpose of the PinPoint program is to integrate adaptive beamforming techniques for co-channel interference cancellation with Time Difference Arrival - Differential Doppler (TDOA-DD) processing for rapid and precise geolocation of low-power tactical emitters in a dense co-channel environment. The end goal of the PinPoint program is to demonstrate the battlefield imaging technology required to provide the commander with a highly sensitive, robust, precise and real-time geographical awareness of the tactical emitter scenario. The PinPoint program is structured as a multi-phase effort beginning with the Phase 0 study reported on herein. The PinPoint Demonstration System will be developed in Phase 1, currently under contract. In Phase 2 the system will be integrated with a suitable multi-antenna collection system such as, but not strictly limited to, LBSS or the Army Testbed Unit. Flight testing is planned for Phase 3. The Phase 0 program was a feasibility study to identify and address the critical technology risk areas associated with integrating beamforming with precision geolocation, through a combination of analysis, algorithm development, simulation, and architecture trades.

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Executive Summary.

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The PinPoint program is structured as a multi-phase effort, beginning with the Phase 0 study reported on herein. The *PinPoint Demonstration System* will be developed in Phase 1, currently under contract. In Phase 2 the system will be *integrated with a suitable multi-antenna collection system such as, but not strictly limited to, LBSS or the Army Testbed Unit.* Flight testing is planned for Phase 3.

The Phase 0 program was a feasibility study to **identify and address the critical-technology risk areas** associated with integrating beamforming with precision geolocation, through a combination of analysis, algorithm development, simulation, and architecture trades. The primary accomplishments include:

- **Algorithms** were developed for **adaptive beamforming and TDOA-DD geolocation** processing, that are cued by signal-up detection at one or more platforms, for both **conventional and LPI** signals;

- **Performance analyses** were made via functional simulation for signal-up (cuing) detection footprint and geolocation accuracy, **with and without beamforming**, for tactical HF and VHF corps-echelon scenarios, for both **stand-off (ACS) and stand-in (TUAV)** geometries;

- **Tactical HF conventional and LPI geolocation** was addressed, and geolocation-aided LPI tracking was shown to **robustly solve the difficult HF Single Sideband-LPI problem**;

- Low-power **(1 watt) tactical VHF** single-channel push-to-talk emitters, both **conventional and LPI**, were shown to be robustly detectable and geolocatable to high precision **(80 m at 50% CEP)** with short collects **(2 sec)** in **strong television interference** environments, across the entire corps-echelon battle area **(250 km past FEBA)** from safe standoff distances;

- The multi-sensor collection system requirements to support PinPoint were found to be compatible with those typical of modern DF, beamforming and TDOA-DD systems; and

- The PinPoint Demonstration System requirements, hardware and software architecture were defined, culminating in an *architecture definition of the Phase 1 PinPoint Demonstration System.*

The essential conclusion drawn from the Phase 0 study is that adaptive beamforming is indeed readily integrated with precision TDOA-DD geolocation. Precision geolocation of individual emissions is made possible, with a high probability of intercept, which in turn yields greatly enhanced emitter tracking and network analysis capabilities. **This combination of technologies yields a dramatic improvement in real-time situational awareness and battlefield mapping,** and *provides the battlefield commander with a precise, real-time display of the tactical emitter locations and current activity, in the dense and highly dynamic emitter and interference environment typical of the modern military engagement.*

1. Introduction.

The purpose of the PinPoint program is to integrate adaptive beamforming techniques for co-channel interference cancellation, with Time Difference of Arrival – Differential Doppler (TDOA-DD) processing for rapid and precise geolocation of tactical emitters in a dense co-channel environment, as illustrated in Figure 1. The end goal of the PinPoint program is to demonstrate a complete "battlefield imaging" capability whereby precision geolocation is incorporated automatically into each signal report in order to provide complete and real-time geographical awareness of the signal environment.
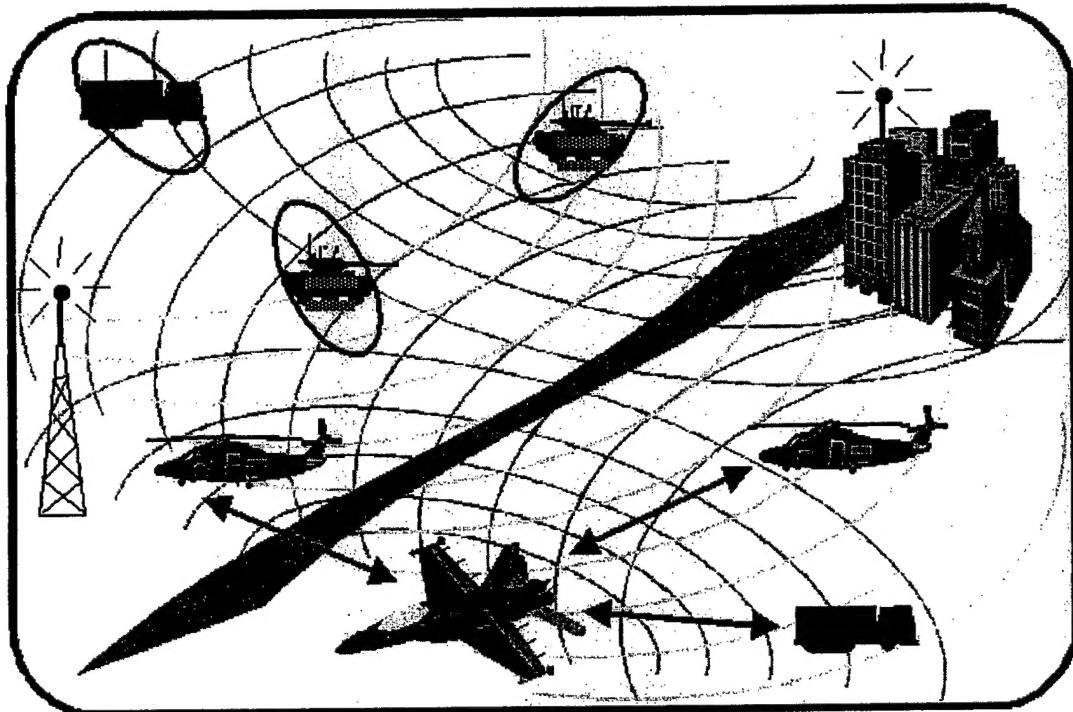
Figure 1. Battlefield Precision Geolocation in an Interference Environment.

Interference cancellation improves SIGINT performance on several fronts. The signal detection range is greatly increased, and the signal is copied from multiple platforms independently with high fidelity, which substantially reduces the TDOA-DD signal processing complexity and data link bandwidths. The short collect times reduce complexity, latency, and link bandwidth, and also ease the motion compensation requirements. Geolocation tasking is simplified as well, and it becomes very feasible to obtain a precision geolocation on each signal-up. As a result, geolocation can be used to assist the downstream processes, such as report association, tracking, and net formation.

1.1 PinPoint Program Overview

The overall PinPoint Program objective is to develop a flight-worthy LBSS-compatible Battlefield Mapping System incorporating interference cancellation and precision geolocation techniques. The current plan is to demonstrate the system with flight tests via links to two or three LBSS-compliant systems, one being the Testbed Unit currently under development for the Army. Alternatively, the PinPoint capability can be integrated into other multiple-antenna collection platforms, although substantial modification of the front-end signal processing algorithms may be required for efficient operation with non-LBSS collection systems.

The overall PinPoint program notional timeline (subject to Army PM approval) is shown in Figure 2. A phased approach is taken, with demonstrable milestones at the end of each phase. The PinPoint Phase 0 effort seeded the overall program with a feasibility study that defined the specific algorithms and assessed their performance in realistic interference environments.

The Phase 1 Task, recently under contract, develops the PinPoint Demonstration System hardware and prototypes the signal processing and HMI software. Testing will be performed in the Matlab environment, with carefully simulated test data incorporating real-world effects such as nonlinear platform motion, array and receiver non-idealities, signal modulation errors, and navigation errors.
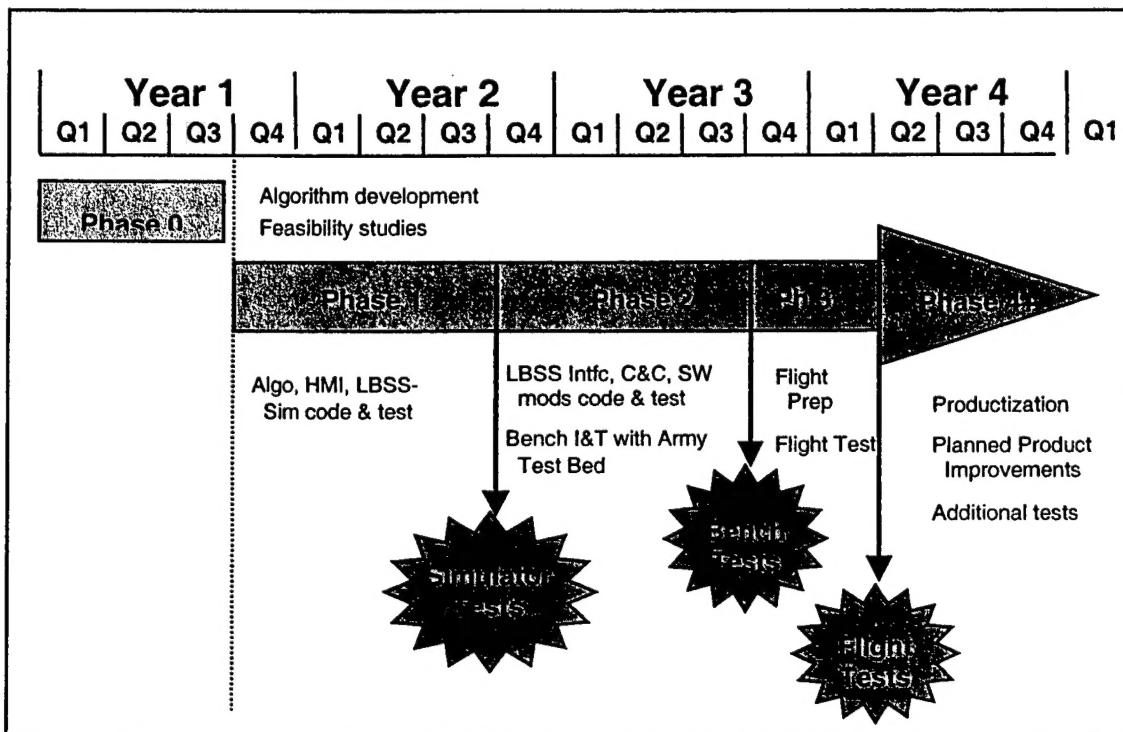
Figure 2. PinPoint Program Timeline (Notional).

During Phase 2, we currently plan on integrating the PinPoint system with the Army Testbed and an LBSS (if available), for bench tests in mid-2002. After Phase 2, the system will be ready for

fielding with the demonstrated capabilities. Phase 3 entails the flight test preparations, flight tests, and data analysis. Additional capabilities (more signal types, improvements for greater data-link efficiency, tailoring to specific platforms) are addressed in follow-on phases.

The PinPoint program plan is shown in relation to other related Radix programs and program plans, particularly the ongoing LBSS program and the current and anticipated Radix efforts in support of the Army, in

Figure 3. The Army Testbed Unit will be needed for integration about midway through PinPoint Phase 2. Also during Phase 2, the signal classifier being developed for the Army under the NRC program can be integrated onto the PinPoint hardware to demonstrate a joint classify-geolocate capability during the flight tests.

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Ice Ax Flt. Test	▲						PPI	
JASA-LBSS*		LBSS DU					LBSS Prod	
Army Testbed*					ATU	Flight Tests		
PinPoint*					Ph 0	Ph 1	Ph 2	FT
NRC*					1a	1b	2	
Prophet*						Phase 1		2

*Future schedules/dates subject to Army PM coordination/plans
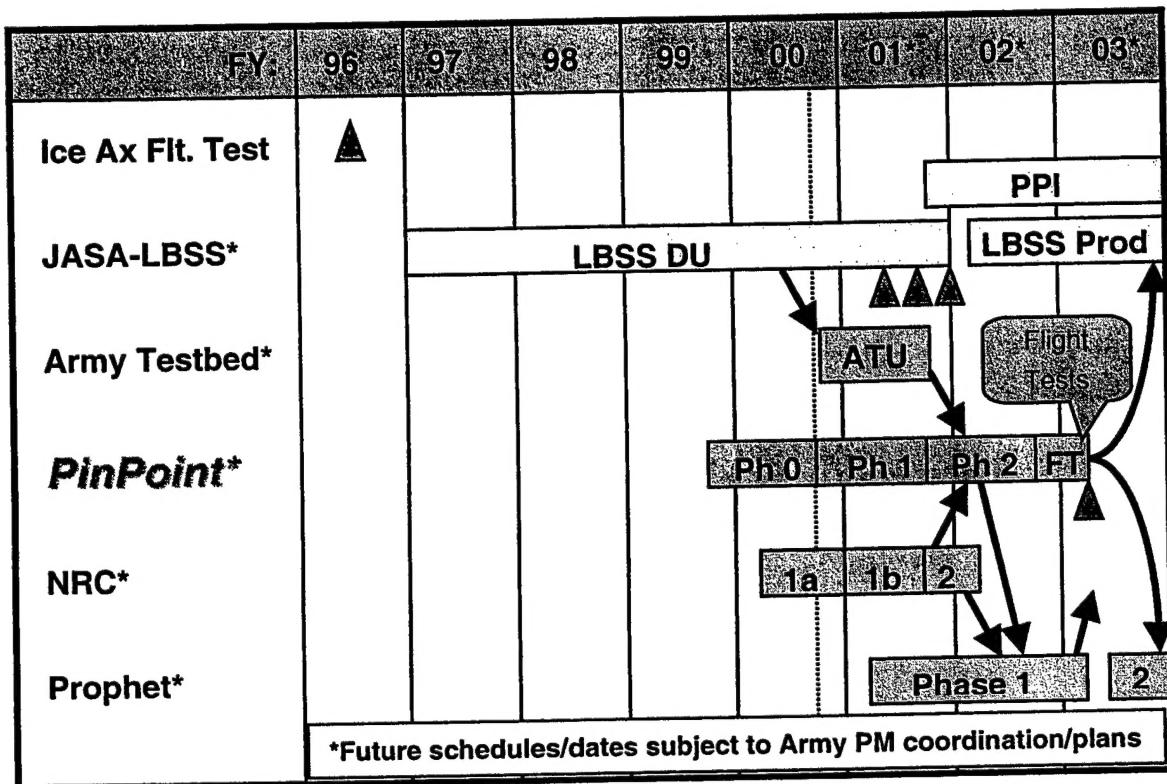
Figure 3. Radix Multi-Program Synergistic Plan (Notional).

After successful flight testing, the PinPoint capability can be channeled into the SIGINT payload for the ACS platform, and the Tactical UAV payload (currently Radix IRAD) in support of the Prophet Air program.

PinPoint technology is highly relevant to the two primary Army airborne-SIGINT thrusts. The technology integrates directly and seamlessly into the payloads Radix is proposing for these efforts, but can also be integrated with other payloads that support adaptive beamforming.

1.2   PinPoint Phase 0 Task Objectives

The Phase 0 program was a feasibility study to identify the critical-technology risk issues associated with integrating beamforming with precision geolocation, and to address those issues with algorithm development, performance analysis and preliminary architecture trades. Specific task objectives included:

- Development of algorithms for combined beamforming and TDOA-DD processing, that are cued by signal-up detection at one or more platforms;

- Performance analysis for signal-up (cuing) detection footprint and geolocation accuracy, with and without beamforming;

- Specifically address tactical HF conventional and LPI geolocation, including geolocation-aided LPI tracking;

- Specifically address geolocation of low-power tactical VHF single-channel push-to-talk emitters in strong television interference, both conventional and LPI;

- Definition of calibration and compensation requirements to support PinPoint;

- Definition of platform motion compensation requirements and supporting techniques;

- Preliminary definition of data link requirements to support PinPoint; and

- Preliminary definition of the PinPoint demonstration system requirements, hardware and software architecture.

The primary signal and interference environment addressed in the study was the VHF tactical single-channel, push-to-talk (PTT) radio operating under television interference (TVI). Both conventional and LPI emitters were addressed. This scenario alone covers the bulk of the airborne SIGINT operational requirement, and demonstrates the extreme need for co-channel signal processing in tactical environments from airborne collection platforms. Furthermore, performance against other signal types and in other environments can be readily inferred from the VHF tactical PTT scenario results.

1.3   Phase 0 Summary of Results

Geolocation accuracy was quantified as a function of target position, platform position and velocity, multiple-antenna array geometry and TVI location with a planar TDOA-DD Geometrical Dilution of Precision (GDOP) error calculation over a 400 km by 550 km grid. A three-platform case is shown in Figure 4, representing the performance of ACS collection platforms against a VHF tactical LPI signal in an environment consisting of three strong co-channel TV stations.
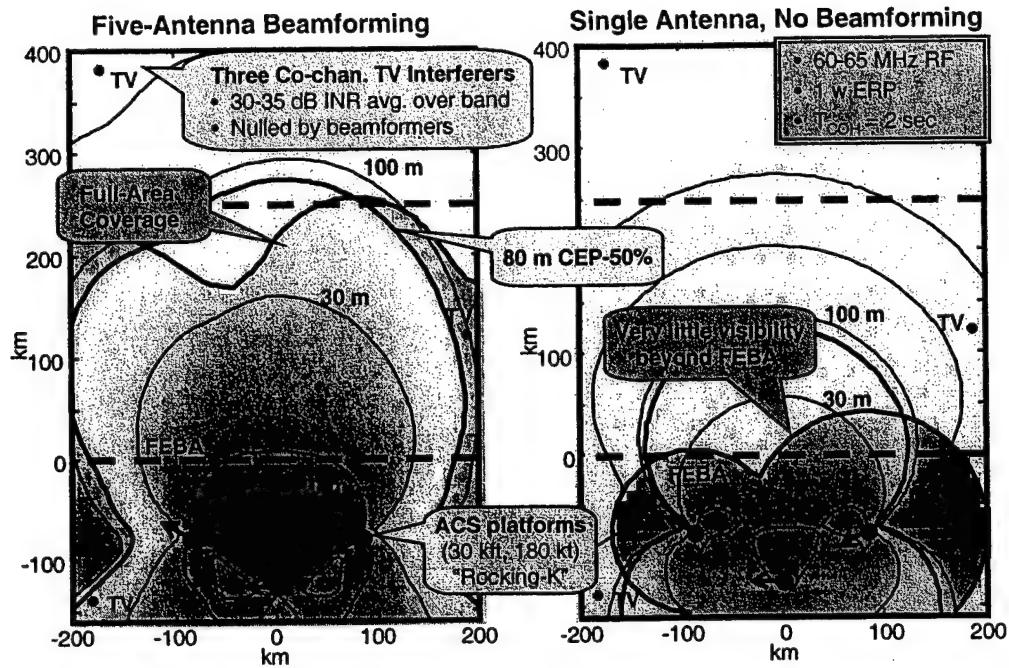
Figure 4. Precision Geolocation, With and Without Beamforming (VHF-LPI).

The platforms are flying at an altitude of 30 kft with a velocity of 180 kt. Location accuracies of 100 meters (50% CEP) are obtained from a two-second collect at ranges of 300 km and more, yielding full target visibility and precision mapping approximately 250 km beyond the FEBA, from a safe standoff distance of over 50 km. Similar performance is obtained with single-channel conventional signals as well. In contrast, without interference cancellation, detection ranges in the presence of typically strong TV interference are greatly reduced, and barely extend beyond the FEBA at all for the low-power (1 watt) emitters.

The functional analysis included models for non-ideal on-platform antenna responses due to nearfield coupling, array calibration errors, beamformer adaptation errors in dynamic environments, and realistic ground to air propagation losses. Error budget values and models representative of LBSS were also included for navigation accuracy, timebase stability and receiver noise figure. A detailed discussion of the error models used in the study are given in Section 4, and itemized in P-50 images are also indicated.

Algorithms were developed for making wideband and long-duration coherent TDOA-DD measurements for LPI and conventional signals through their respective beamformers. The beamforming algorithms and corresponding PinPoint geolocation accuracies are discussed further in Section 5 for conventional signals, and Section 6 for LPI signals. These performance results are extrapolated to additional, similar signal types in Section 7. The baseline approaches for combining the TDOA-DD measurements into target latitude-longitude are discussed in Section 3.

The receiver TDOA compensation and master oscillator (long-term) phase stability requirements for PinPoint are similar to those required for single-antenna TDOA-DD processing. The receiver dynamic range, isolation, phase stability and local oscillator (short-term) phase noise requirements are driven primarily by the adaptive beamforming null depth requirements.

The essential conclusion drawn from the Phase 0 study is that beamforming is readily integrated with precision TDOA-DD geolocation and yields a dramatic improvement in battlefield mapping capability by both increasing the signal-up detection footprint to cover the entire battlefield, and by reducing the required signal collection time for precision geolocation at long ranges to very manageable levels. At signal levels near the (co-channel) detection threshold, accuracies are similar to what would have been obtained via conventional single-antenna TDOA-DD processing in-the-clear, at the beamformed SINR. Even for stronger signals at closer ranges that are easily detected without beamforming, the location accuracy is substantially improved by beamforming in a co-channel environment, as seen in Figure 4.

2. PinPoint Demonstration System Architecture.

As a part of the Phase 0 study effort, the PinPoint Demonstration System architecture, concept of operation, and overall development plans were further defined. The system hardware, baseline concept of operation and capabilities, and possible capability extensions are discussed in the following sections.

2.1 Hardware Architecture

The PinPoint development and demonstration system hardware is currently planned to consist of a VME chassis, a VME controller with Ethernet, and a Sky Mercury dual PowerPC (G4) card loaded with 128 MB of memory, with a Sun workstation as an operator console and display unit. This system will interface to LBSS-compliant hardware through standard 100-base-T Ethernet connections. The planned configuration for eventual flight testing is shown in Figure 5, where the PinPoint hardware is interfaced to the Army Testbed (a fully flight-worthy but reduced-scope LBSS-compliant system) and a full LBSS through Ethernet-compatible bidirectional airlinks. The PinPoint system will have dedicated control of the Testbed, and similarly dedicated control over an equivalent set of assets on the LBSS platform when available, during the PinPoint flight tests.
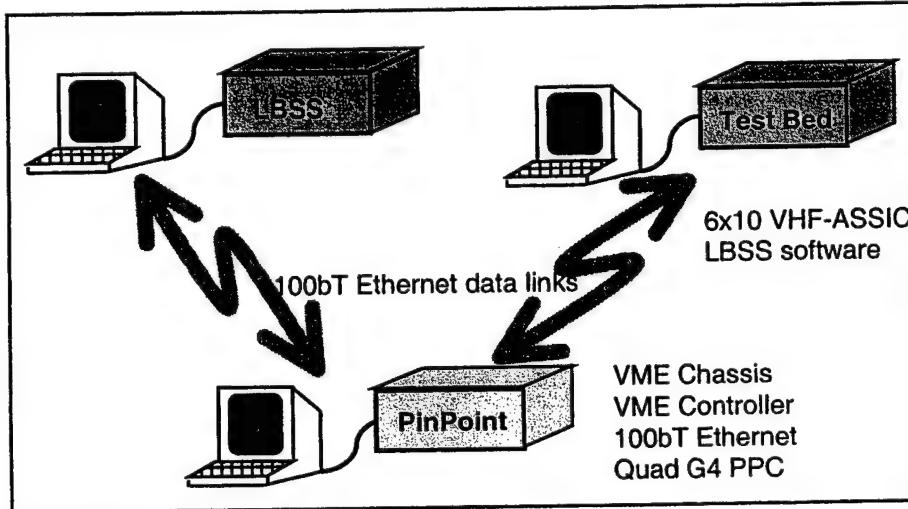
Figure 5. PinPoint Demonstration and Flight-Test System.

The hardware design is to be finalized and the hardware procured under Phase 1. If a COTS G4 card can be obtained that also includes the VME controller, RaceWay and Ethernet functions, then only one card will be required for the PinPoint system.

2.2 Baseline Concept of Operation

The baseline PinPoint Demonstration System is currently being designed to support flight testing with up to three LBSS-compliant platforms with hardware and software configurations

essentially equivalent to those of the Army Testbed. Other multiple-antenna front-end systems could be supported in lieu of LBSS, but the PinPoint capability may be degraded if the appropriate front-end algorithms are not implemented on the platforms. In particular, the automatic geolocation tasking mode may degenerate to single-antenna processing only, or disappear entirely. Link bandwidth requirements may grow substantially also.

The system architecture maximizes usage of the existing LBSS functions hosted on the Army Testbed, with minimum modification of the LBSS code. In particular, existing capability for Built-In Test (BIT), automatic copy cuing, directed-search and general-search reporting, pre-D data acquisition, navigational data acquisition and receiver TDOA compensation will be exploited. Any new LBSS commands needed, e.g. for acquisition of internal data not currently output but needed for TDOA-DD such as digital-receiver LO phase data, will circumvent the primary LBSS interfaces through direct communication to modified software modules in order to minimize "ripple-down" impacts on other LBSS software, particularly the existing back-end report processing.

The baseline system capability will include three-platform TDOA-only and two- and three-platform TDOA-DD processing of single-channel conventional and LPI tactical (e.g. push-to-talk voice/data) signals. The LBSS automatic copy cuing (ACC) capability will be used to generate locations automatically for each signal-up of high interest, and manual tasking modes will be available as well for operator-initiated location requests.

The baseline capability for conventional signals will include both automatic and operator-initiated processing of signals when detected by one or more platforms. Multi-antenna geosort (geolocate-before-detect) processing will be available upon operator request to cover cases where some or even all of the platforms cannot successfully lock a beamformer onto the desired conventional signal, and/or for operator-cued geosort-based environmental search.

Automatic geolocation of conventional signals will be implemented by ACC tasking of each platform to provide beamformed, pre-demod data for each new high-interest signal-up detection received by that platform. When one platform detects a signal and the other does not, a spatial (multi-antenna) pre-demod collect for the other platform(s) is tasked. Conventional signals are associated across platforms based on coincidence of time-of-detect (up-edge) and frequency, and the data is cross-correlated over a pre-defined collect duration (nominally one or two seconds) to make the required TDOA-DD measurements.

Operator-initiated geolocation processing of conventional signals will be implemented by tasking each platform for pre-demod copy or multi-antenna data, over a specified acquisition window. Association of multiple co-channel signals is made by comparing the cross-correlation normalized magnitudes between multi-target beamformer outputs, if other means (e.g. signal classification) are either unavailable or fail to resolve all ambiguities.

The baseline capability for LPI signals will include both automatic and operator-initiated processing of signals that are detected and tracked by two or more platforms. In either case, each platform is tasked to downlink beamformed, tracked, pre-demod data for the designated LPI signal of interest, for a defined collect duration (nominally one or two seconds). In automatic

mode, this data is downlinked starting with track initiation. Coincident LPI transmissions are associated across platforms by comparison of the tracked signal externals.

2.3   Pre-Planned Product Improvements

The baseline PinPoint capabilities directly address precision geolocation of single-channel push-to-talk tactical emitters, which comprises the bulk of the tactical Army SIGINT battlefield mapping requirement. Plans are in place to extend these capabilities for complete coverage of all current and future signals of tactical interest, and to expand the coverage of LPI single-channel emitters as well. These plans are itemized below:

Integration with Signal Classifier. The Radix NRC Signal Classifier, being developed for the Army on another contract, is an ideal candidate for integration with PinPoint to provide a combined signal classification-geolocation capability. It is currently anticipated that this integration will take place through Army inter-office cooperation and coordination at Radix, within the scope of the ongoing multi-phase PinPoint and NRC programs, and in time for the PinPoint flight tests.

LPI Single-Platform Detection Capability. The baseline system geolocates LPI emitters only when detected and tracked by multiple platforms. With additional software and low-latency cuing and/or additional memory, geolocation can also be performed when only one platform detects and tracks an LPI emitter, by tasking other platforms to acquire and downlink multi-antenna pre-demod data in the same manner as that used for conventional signals that are detected and beamformed by only one platform in the baseline system.

Coherent Paradigm Compression. Compression techniques have been developed for analog FM Voice that efficiently demodulate and pack the data in such a way that the pre-demod waveform can be phase-coherently reconstructed. Similarly, digital signals can be highly compressed via coherent demod-remod techniques, with the aid of fine signal external features measurement.

On-Platform Geolocation Processing. The PinPoint link bandwidth requirements can be reduced substantially for the case where one platform detects the signal and the others do not, by transferring the paradigm from the detecting platform to the non-detecting platforms rather than by downloading multi-antenna pre-demod data. The link bandwidth is decreased not only by a factor of the number of antennas but also by the reduction in dynamic range required for beamformed paradigms versus raw antenna data containing both signals and interference.

HF SSB-Voice LPI Processing. Incorporate coarse geolocation into the LPI tracker function, for a dramatic improvement in overall processing performance against the SSB-Voice LPI emitters commonly found in the HF bands. See Figure 15.

HF SSB-Data Conventional Processing. Integrate specialized detection, classification and beamforming techniques with precision geolocation for the class of multi-tone SSB-Data signals often used in modernized HF ALE networks such as Link-11.

RSSS Drop Receiver Support. Add command and control software to automatically task assets for beamforming and geolocation of high-interest signal detections made by the LBSS wideband scanning function (RSSS).

Special TDMA Net Capability. Incorporate specialized net tipoff, verification, synchronization, and beamforming algorithms with geolocation for the mapping of special TDMA nets of high interest to the Army. See Section 7.2.

These capability enhancements may be undertaken after flight-testing of the baseline system. Alternatively, some or all may be taken on in parallel with the current effort, with some extension of schedule and increase in funds, for a more comprehensive set of flight tests.

3. PinPoint Precision Geolocation Approach.

The PinPoint approach to geolocation is based on the integration of multi-platform TDOA-DD processing with adaptive spatial beamforming for interference cancellation. The spatial rejection of co-channel interference enables precision signal geolocation measurements to be made on signals at power levels well below the co-channel interference using relatively short collects, similar to the collection times that would be required in the absence of interference.

The inter-platform TDOA-DD measurements are obtained coarsely via cross-correlation in delay and doppler of the preprocessing beamformer outputs, at delay-doppler resolution corresponding to the beamformer weights adaptation interval and bandwidth. DF triangulation may be used to cue the initial TDOA-DD search space. Fine geolocation is then obtained by coherent integration of the beamformer cross-correlation results across the full signal measurement time-bandwidth.

3.1 TDOA-DD Geolocation Solution, Two Platforms

The time difference of arrival (TDOA) between two platforms is a function of platform and target position. The differential Doppler (DD) is the time-derivative of TDOA. Over short-duration collects over which the higher-order platform motion effects can be neglected, and assuming free-space propagation, both TDOA and DD may be computed as functions of the (assumed constant) platform and target positions and velocities. The basic geolocation problem is to invert this multivariate transformation from TDOA-DD measurements to target location (and, in general, velocity), given the known (and assumed constant) collection platform positions and velocities.

If the target is stationary, the two-platform geolocation transformation (from target lat-long to TDOA-DD) is well-defined in closed form and can be readily computed. The inverse transformation is generally not defined in closed form, and must be inverted numerically on a case-by-case basis. A table lookup can be used for coarse geolocation, followed by iterative inversions of the first-order approximation (multi-dimensional derivative, or Jacobian transformation) computed about each successive target location estimate. With modern floating-point DSP co-processor technology, it is also computationally reasonable and more conceptually straightforward, especially when incorporating terrain and platform motion into the calculations, to interpolate and recompute the forward (lat-long to TDOA-DD) transformation over small, successively finer grids, iteratively narrowing down onto the final location estimate.

Geolocation ambiguities can also exist, where more than one location gives rise to the same set of TDOA-DD values. An example is given by the inherent left-right ambiguity when the two platforms fly in the same line at the same speed. DF data is required in general to resolve such ambiguities with a single look, but other means may be possible on case-by-case bases, such as geographical constraints and/or multiple looks at the emitter from sufficiently different collection geometries.

3.2   TDOA-DD Geolocation Solution, Three Platforms

When three platforms have target visibility (i.e. can detect and beamform on the signal and/or obtain a detectably strong TDOA-DD cross-correlation peak), the inter-platform TDOA-DD data comprise four independent measurements. The TDOA data (over short collects) depends on the target and platform positions alone, while the DD data depends on both positions and velocities of the platforms and target. Moving targets can therefore be geolocated by TDOA, and their velocities can then be estimated by DD.

The geolocation problem for targets known to be stationary is overdetermined by three-platform TDOA-DD data, and therefore provides greater accuracy through statistical averaging. Multiple two-platform TDOA-DD locations can be optimally combined based on the estimated error statistics, but the formulation is complicated because of the statistical dependence of the errors. A simpler approach is to compute two target location estimates, one from the TDOA data and one from the DD data. The resulting locations are statistically independent and therefore easily combined based on their estimated error ellipses (see Chestnut, [2]) because of the statistical independence of the underlying TDOA and DD measurements.

A combined approach for three-platform collects is to first assume the target to be moving and estimate its position and velocity. If the velocity measurement is statistically indistinguishable from zero, the DD-based position (assuming exactly zero target velocity) is computed and combined with the TDOA-based position for an improved location estimate. This approach has high merit in a dynamic scenario if there is a substantial a-priori probability that the target is truly stationary, and especially if the velocities of moving targets are also relatively high in the majority of cases, e.g. with stationary vs moving vehicles.

If the target appears to be stationary but is actually slowly moving, as could be the case with a pedestrian-held emitter such as a cell phone, the combined TDOA-DD location estimate will not be substantially less accurate than the TDOA-only location estimate. However, the TDOA-DD estimated error ellipse will be too small, giving a false illusion of higher accuracy. In this case, the TDOA-only error ellipse would be representative of the true location error.

3.3   Platform Motion Compensation

Precision differential Doppler (DD) measurements ordinarily require coherent collections of 1 second or more in duration, while good interference nulling requires beamformer update intervals on the order of 0.1 second or less. The signal DD can generally be assumed constant during a beamformer update, with no consequences beyond a negligible degradation in coherent integration gain due to a slight differential phase chirp across the interval, even under severe lateral platform accelerations due to turbulence. Platform motion effects need be compensated for only in the longer-term coherent integration of the beamformer cross-correlations.

Motion compensation is performed during fine geolocation by integrating the beamformer cross-correlations, computed at the cued TDOA-DD point(s), in fixed-geolocation (target lat-long) coordinates instead of fixed-TDOA-DD coordinates. Navigation (position, velocity) data can be smoothed to remove high-frequency jitter/noise components and resampled at the beamformer

update rate for computation of the TDOA-DD coherent-integration differential-phase reference sequences.

Terrain elevation is also readily taken into account in the fine-geolocation computations when the fine integration is performed in fixed-lat-long coordinates.

4. Precision Geolocation Error Analysis.

The geolocation error analysis for the Phase 0 study is based upon identifying and quantifying error sources for the underlying TDOA-DD measurements. These measurement errors are then converted into position errors for a given collection platform geometry via the linearized target-position-to-TDOA-DD transformation. For the purposes of location error ellipse computation, all platforms and targets are assumed to lie in a two-dimensional (x-y) plane.

The location error ellipse is converted to a circular error of 50% (CEP-50) under the assumption that the errors are jointly Gaussian (see, e.g., Torrieri [3]). The CEP-50 is calculated for each candidate target position over a grid covering the battlespace, and plotted as an image with color representing the error radius and overlaid contours, as shown in Figure 4.

Some of the primary error sources identified in Phase 0 are shown in Table 1 and discussed in the following sections. The errors quantified in the CEP-50 images are also indicated.

Error Source	Section	Treatment in CEP-50 Analysis Plots
SINR	0	Propagation loss models, ideal beamformer gains
Navigation Data	4.2.1	GPS-aided Nav: 10 m, 0.1 m/s rms
LO Stability	4.2.1	GPS-disciplined Rb model, from vendor-supplied data
Receiver Group Delay	4.2.2	Assumed negligible after TDOA compensation
Antenna Coupling	4.2.3	Emperical, cal-derived models (VHF): antenna group delay, wideband frequency response.
Interference Correlations	0	Not included
Ground Multipath	4.4	Not included
Target Motion	4.5	Assumed identically zero, for TDOA-DD

Table 1. Geolocation Error Sources Addressed in Phase 0.

4.1   Noise Errors

The TDOA-DD random measurement errors due to additive white Gaussian noise are readily quantified in terms of the signal collection bandwidth, noise bandwidth, and coherent and noncoherent integration times, as given in Stein [1]. Since the signal is assumed to have detectable beamformed SINR as seen from at least one platform, the dominant error terms are due to signal-noise correlations and the noise-noise correlation term can be safely neglected. Thus, the error analysis equations can be derived as if all platforms compute correlations against a known paradigm, which significantly simplifies the treatment of the three-platform case.

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The signal SNR at each platform is computed assuming ideal beamforming weights and Gaussian interference statistics, for the array geometry being used by that platform and its observed interference field. The array response to the signal of interest and to non-TV interferers (e.g. at HF) is determined by assuming ideal, omnidirectional elements.

The interferers at VHF are modeled as television stations, which are predominantly horizontally polarized, whereas the signals of interest, and receiving array elements, are predominantly vertically polarized. The array cross-pol response is modeled as a random gaussian process for purposes of computing the array TV response, and the resulting beamformed patterns exhibit little recognizable nulling in the direction of the TV stations, in the vertical response. Thus, a vertically polarized signal at the same angle of arrival of a strong TV interferer is not nulled; instead, response at all angles of arrival is degraded slightly due to polarization mismatch.

Propagation losses for both signal and interference are interpolated from curves given in CCIR Resolution No. 22 [4]. These curves were originally generated from formulas given by Norton in [5], [6]. These data were spot-validated at certain frequencies and altitudes, near the long range detection limit for representative tactical emitters, during the Ice Ax flight tests.

4.2   Instrumentation Errors

The instrumentation errors considered under Phase 0 include collection platform position and velocity errors, local oscillator and reference stability, receiver group delay variations across the array and across platforms, and the nonidealities in the platform-mounted array responses due to nearfield coupling.

4.2.1   Navigational and Timebase Accuracy

Precision geolocation requires accurate a-priori knowledge of the collection platform positions and velocities. Highly accurate GPS-augmented intertial navigation systems are readily available, and are small and light enough to be included even in a TUAV payload. These systems yield absolute position and velocity accuracies of 10m and 0.01m/sec rms. For purposes of CEP calculation, these errors are assumed Gaussian and independent between platforms. In actual practice, the errors are slowly varying for a typical collection platform, and would act more like geometry and time dependent bias errors or distortions in the battlefield map.

The accurate measurement of differential Doppler requires highly accurate frequency references. At typical platform velocities, precision geolocation requires frequency measurement accuracies on the order of 1 mHz at 100 MHz, requiring a local oscillator fractional stability on the order of 10^{-11}. These stabilities are readily maintained across platforms with Rubidium cell reference oscillators. Accurate absolute time is maintained at all platforms for accurate TDOA over the mission duration, by locking these references to GPS time.

A low-cost platform with poor navigation and timebase accuracy is of little direct use as a precision geolocation platform, but can be used to gather a paradigm for correlation at other standoff platforms with accurate navigation/timebase systems.

The master oscillator stability error model used in the CEP calculations represents the short-term frequency stability of the LBSS local oscillators locked to the GPS-disciplined Rb reference used on platforms currently targeted for LBSS deployment. The model is derived from vendor data, given primarily in the form of Allen variances of the component oscillators, and the various phase-locking loop gains and bandwidths used in LBSS. A treatment of Allen variance and frequency reference stability is given by Barnes, et al. in [7]. The resulting model is given by:

$$\delta_{rms} = 1.5 \times 10^{-11} \left(\frac{1}{T_{coh}} + \frac{\sqrt{BW_{neq}}}{f_c} \right)$$

where:

δ_{rms} = fractional frequency error at a single platform (standard deviation);

T_{coh} = coherent integration time for DD measurement (seconds), $0.1 < T_{coh} < 10$;

BW_{neq} = measurement (channel) noise bandwidth, in kHz; and

f_c = signal carrier frequency, or channel center frequency, in MHz.

The LBSS oscillators are specifically designed to support TDOA-DD geolocation using readily available parts, so this model can be considered representative of other precision TDOA-DD platforms as well.

4.2.2   Receiver TDOA Compensation

Most modern receivers employ SAW filters to achieve the passband-to-stopband ratios required for low aliasing when digitizing directly at IF. These devices in particular have substantial bulk group delays, on the order of microseconds, and can vary considerably from device to device, and as a fuction of temperature. Accurate geolocation requires matching of the measurement delays between platforms to within nanoseconds.

The CEP analyses assume that the signal collection receivers are calibrated for group delay accurately enough so that any residual errors are negligible. This assumption is based on current LBSS receiver technology, and may not necessarily translate to arbitrary collection systems unless TDOA compensation capability is added. In particular, many DF systems employ a random noise or sinusoidal source for channel phase matching, which does not address the common-mode wideband frequency response or narrowband group delay across the receivers.

The LBSS receiver compensation signal is a BPSK-modulated sinusoid, with carefully controlled synchronization between the modulating switch and the GPS timebase. This source allows the narrowband group delay and/or wideband frequency response to be measured in the absolute sense for each receiver channel via correlation with the known source waveform. TDOA compensation data can be acquired over the desired bandwidth before, during, and/or after a TDOA collect by so tasking the LBSS system.

For conventional signals, the TDOA compensation data would nominally be acquired at or near the observed signal frequency and bandwidth immediately after the collect, and would be used to

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measure the actual receiver group delays on the signal. These group delays are combined using the beamformer weights to determine the average group delay through the beamformer.

For LPI signals, the TDOA compensation data would be acquired across the full collection bandwidth and used to generate absolute frequency-response tables as well as an overall, average group delay.

Frequently revisited bands, such as tactical-VHF, may be compensated over the entire band according to a set schedule rather than individually with each TDOA-DD collection. In that case, the absolute frequency-response data is collected and group delays over the conventional-signal bandwidths are computed as needed. The frequency response data can also be temporally smoothed to improve accuracy.

4.2.3   Array Calibration

Array calibration is required for computation of DF, which is used for cuing the geolocation search as well as resolving ambiguities. The primary PinPoint tactical signals of interest are readily processed with vertically polarized DF arrays and single-pol DF calibration tables.

Single-pol array calibration data acquired during Ice Ax flight tests was analyzed to determine representative models for nearfield coupling effects on the antenna angle-frequency responses. The statistical distribution of the group-delay between each antenna and the reference antenna across frequency and angle is shown in Figure 6, and exhibits an exponential rolloff.
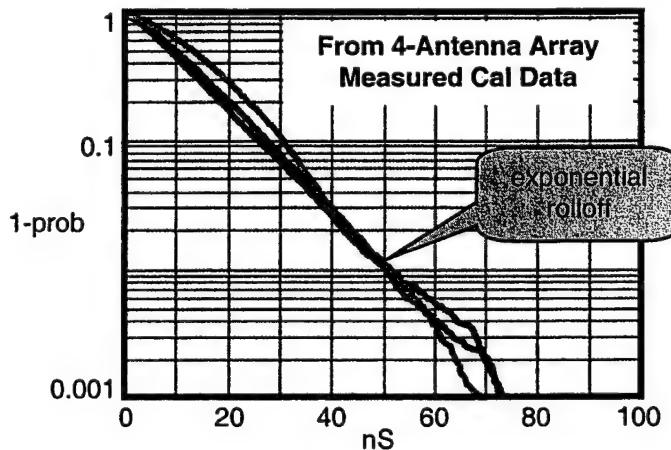
Figure 6. Antenna Group Delay Statistics for Representative VHF Array

These data infer a root-exponential delay distribution for individual antennas, which was used to generate representative antenna frequency responses and calibration errors at fixed angles for use in wideband LPI simulations. The data also imply the existence of a group delay error for the reference antenna, which is not ordinarily calibrated out. The CEP analyses incorporate a reference-antenna group delay error term of 12 nS rms to account for this source of error.

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4.3 Interference Correlation Errors

With single-antenna TDOA-DD processing, the interference correlations can bias the signal TDOA-DD measurement substantially, even when the SINR is high, when the interference and signal are located sufficiently close together that the correlation lobes intersect on the delay-Doppler plane. Some interferers, notably TV, also exhibit strong correlation sidelobes in delay (and Doppler) at the horizontal retrace interval (and vertical retrace frequency), which can overlap the signal correlation mainlobe and bias the measurement.

Beamforming attenuates the interference and improves SINR, as such reducing the correlation bias errors to no worse than would be obtained with a single antenna at the beamformed SINR.

Television interference correlation errors were investigated for conventional-signal beamforming by examining the coherence of the beamformer residuals against the original TV waveforms over time. Actual TV signal collects were analyzed for auto-correlation sidelobes in delay and Doppler, verifying the horizontal and vertical retrace correlations. FM voice was similarly analyzed, and found to exhibit similar correlation lobes over short-duration collects. However, over longer integration periods, the correlation sidelobes for FM voice tend to average out. With TV signals, a similar effect is likely when the video content is rapidly changing.

Interference correlation errors are not currently modeled in the functional CEP analyses. Additional study would be needed to develop appropriate functional models. The detailed end-to-end simulation capability to be developed under Phase 1 can be used to investigate these effects by direct simulation.

4.4 Multipath Errors

In most cases, the dominant multipath contribution comes from scatterers in the near vicinity of the ground emitter, and each platform sees a different set of dominant scatterers. For narrowband conventional emitters, the path differential delays are far shorter than the signal inverse bandwidth so the primary effect of multipath is to bias the apparent TOA randomly and independently across platforms. The resulting location error is commensurate with the power-weighted rms scatterer distance; i.e. if scatterers with combined power -10 dBc are randomly distributed over a radius of 500 m from the emitter, we can expect a resulting TDOA location error radius of about 50 m. Similar arguments apply to path differential-Doppler and TDOA-DD processing of stationary ground targets.

With moving targets, the scattered path Doppler varies over $\pm v_{tgt}/\lambda$ depending on the scatterer location. Moving target velocity estimation accuracy is therefore limited to a relative error no better than the total scattered-to-direct path power ratio.

In mountainous regions and at lower platform altitudes, significant multipath components can come from distant scatterers, with large differential delays and Dopplers. If the corresponding correlation lobes resolve, the direct path component may be identified and correctly geolocated based on signal strength and/or geometric consistency.

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Multipath errors are not currently modeled in the functional CEP analyses. Simple parametrically defined models may be incorporated into the Phase 1 end-to-end simulation for further study if warranted. A detailed terrain-scattering model is currently out-of-scope for the current Phase 1 effort, but could be readily incorporated later if required.

4.5   Target Motion Errors

The emitter is assumed to be stationary for two-platform TDOA-DD geolocation. If the target is moving parallel to a contour of constant TDOA (a hyperbola, on a flat earth), then to first order the motion does not affect the differential delay and Doppler (delay rate) measurements, and the derived geolocation accurately represents the target position at the center of the collect interval. Target motion orthogonal to the constant-TDOA hyperbola biases the differential Doppler measurement, offsetting the estimated location from the true location some distance along the hyperbola. At typical VHF collection geometries, this location offset varies from 100 to 1000 meters per m/sec of the target velocity component orthogonal to the constant-TDOA curves.

With three or more collection platfoms, a moving target can be geolocated based on TDOA data alone, and its velocity estimated based on that geolocation and the DD data. If the target can be assumed stationary, the location estimate is improved by combining the independent TDOA-only (moving-target) and DD-only (stationary target) geolocation estimates. Especially at the longer ranges, this improvement is substantial since the individual TDOA and DD error ellipses are highly elliptical but intersect at an angle so that the combined error ellipse is much more circular.

If a target is assumed stationary but is actually moving, the DD-only geolocation error ellipse slides off of the target true position, along the major axis of the TDOA-only error ellipse. If the estimated target velocity were statistically indistinguishable from zero, then the corresponding motion error would be statistically indistinguishable from a TDOA-only geolocation error within its highly elongated error ellipse. The combined geolocation measurement is therefore not substantially worse than the TDOA-only measurement in this case, but the estimated TDOA-DD error ellipse indicates an accuracy higher than has actually been achieved.

5. Beamforming Geolocation, Conventional Signals.

Adaptive beamforming for signal detection and collection significantly improves battlefield mapping performance by greatly expanding the instantaneous signal detection footprint and spatially attenuating the interference before geolocation processing. Some of the beamforming algorithms utilized by PinPoint are briefly discussed in the following section. PinPoint geolocation accuracy with and without the use of beamforming is discussed in the following sections, via functional CEP analysis results.

5.1 Blind Beamforming Algorithms

The class of blind beamforming algorithms adapt the weights according to certain pre-specified signal characteristics, without requirement for DF calibration of the array. Signal DF can be computed from the beamforming weights when the array is calibrated, yielding DF accuracies approaching that which would be obtained conventionally, at the beamformed SINR. Some of the beamforming algorithms employed by PinPoint include:

Dominant Mode Prediction (DMP): The primary tactical-VHF co-channel detection algorithm for PinPoint. Signal up (and down) edges are detected beneath interference through rank changes in the short-term covariance matrix. Beamforming weights are generated with each detection, and can be used for DF, to copy short duration signals, or to initialize a beamformer.

Multi-Target Constant Modulus Array (MT-CMA): A multiple-signal beamformer that locks weights to signals with constant amplitude modulations such as FM or PM. Conventional AM-voice and QAM are also captured, since their amplitude variations are considerably less than that of noise (or band-limited TV interference).

Multi-Target Variable Modulus Array (MT-VMA): A multiple-signal beamformer that locks weights to signals with highly variable complex envelopes, particularly SSB-Voice.

General Blind Copy (GBC): Another multiple-signal beamformer that combines signal feature analysis with multiple property maps so as to automatically assign appropriate beamforming adaptation algorithms to various ports, copying all tactical signals of interest.

5.2 Co-Channel DF and DF-based Beamforming

Copy-aided DF (CDF): The primary DF work-horse for tactical-VHF. Individual signals are DF'ed based on their beamforming copy weights, as determined by any of the blind adaptive beamforming algorithms discussed above.

Joint Maximum-Likelihood DF (JML): The "fall-back" algorithm for general co-channel signal detection and DF, used for background environmental survey to find signals that are not edge-detectable either because they fade in and out slowly or are up for very long durations. The algorithm is subspace-based, similar to the well-known MUSIC algorithm, but computes the spatial (DF) spectrum differently and has better ambiguity performance.

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Beamforming weights can also be determined after DF by an algorithm such as MUSIC or JML, based on the array calibration vectors. For weak signals, good performance is obtained using the Wiener-Hopf weights, i.e. by steering the beamformer adaptively based on the desired signal's array calibration vector. For stronger signals, better performance is obtained by directly steering the nulls via projection orthogonal to the array calibration vectors of the interferers. Especially at VHF, i.e. with horizontally polarized TV interference, the latter requires dual-polarized array calibration tables, both for accurate DF of the TV and for good nulling.

5.3   Conventional-Signal Geolocation Accuracy at VHF

The predominant source of co-channel interference in the tactical VHF bands is television. An example of typical airborne-SIGINT television interference is shown in Figure 7. The figure illustrates an "eigen-PAN" spectral display, where the eigenvalues of the channelized covariance matrices are plotted as a function of frequency. This particular display represents the interference floor with respectively zero, one, two, and three co-channel nulls, with a four antenna array.
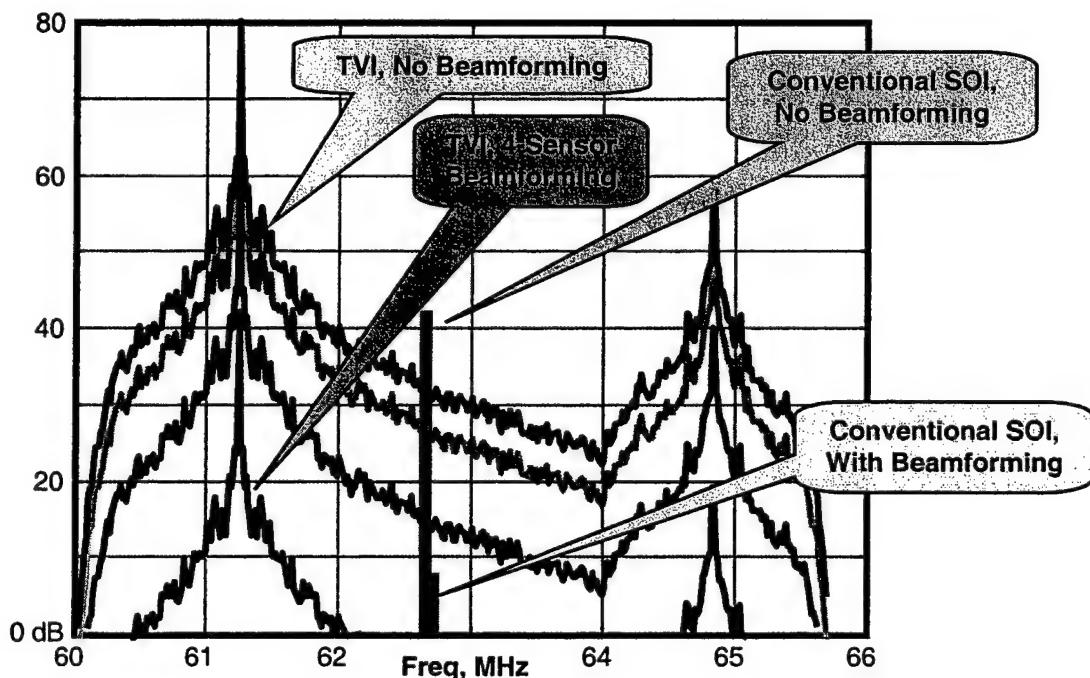

Figure 7. Television Interference Model, Conventional Signals.

The TV spectrum power levels shown in this figure are scaled to represent the three-TV interference environment modeled in the functional CEP analyses for conventional tactical-VHF.

In particular, the average interference to noise level in the absence of beamforming is about 32 dB in a 25 kHz channel, at the test SOI frequency.

Geolocation accuracy with and without beamforming is shown in Figure 8, for a conventional low-power (1 watt ERP) tactical-VHF (60 MHz) emitter in a typical ACS (Corps echelon) collection geometry. The array geometry is that of a typical airborne collection platform and consists of five vertical blade antennas of roughly 1 meter electrical length. The platforms are shown at the centers of their respective tracks in a "Rocking-K" standoff formation, where they approach the forward edge of battle (FEBA) no closer than 40 km at the ends of the outer tracks.
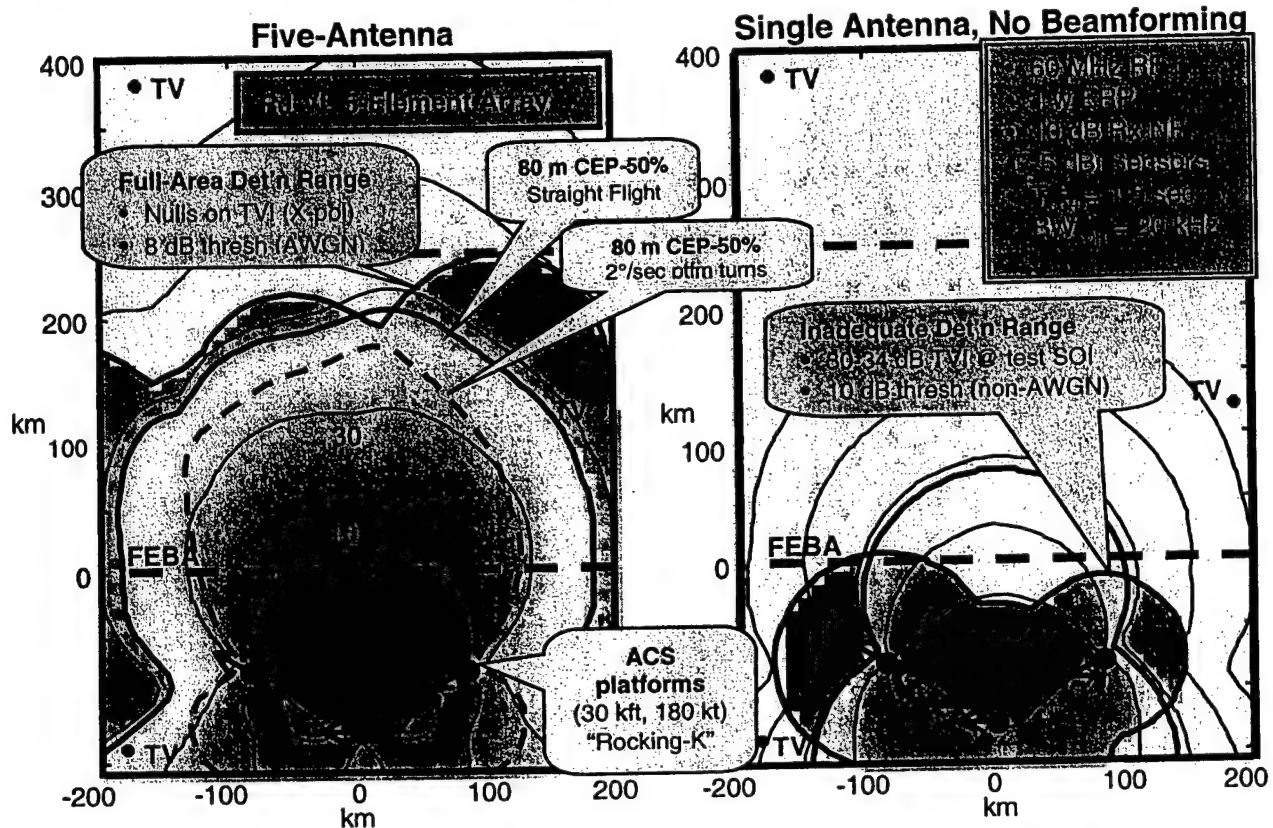

Figure 8. Conventional Tactical-VHF Signal, With and Without Beamforming.

With adaptive beamforming, the signal detection footprint extends to roughly 200 km beyond the FEBA, nearly covering the entire battle area. Geolocation accuracy is better than 80 meters with 50% probability over most of the area, and is no worse than 300 meters at the extremities. Geolocation performance is degraded by a factor of roughly two or three when the platforms turn at a rate of 2 degrees per second, as determined by Monte-Carlo simulation.

Since the TV interference is nulled by the array cross-pol patterns, detection performance is maintained even in the near vicinity of the TV. Geolocation near the TV may not be as accurate as shown, however, due to residual correlations biasing the TDOA-DD measurements.

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Without adaptive beamforming, the detection footprint for the low-power emitter is entirely inadequate, barely extending beyond the FEBA at all. The single-antenna geolocation performance is also weak, exceeding 1000 meters at the further reaches of the battle area and exceeding 100 meters over most of the area. (Single-antenna geolocation beyond the FEBA can be implemented with the aid of a paradigm collected by a stand-in asset such as a TUAV that cannot itself act as a precision geolocation platform due to inaccurate nav/time.)

5.4 Conventional-Signal Geolocation Accuracy at HF

The geolocation accuracy at HF (6 MHz) is shown in Figure 9, again for a Rocking-K ACS formation in a Corps echelon engagement. The eight-element beamforming array represents an HF array used on a typical collection platform, with vertical antennas of one meter electrical length. The interference environment is isotropic environmental and galactic noise typical of the midwestern United States, with a single co-channel tactical emitter of ERP equal to the target emitter (10 watts) located just outside the Corps echelon battle area. The target emitter bandwidth is commensurate with SSB-Voice, and is collected for five seconds.
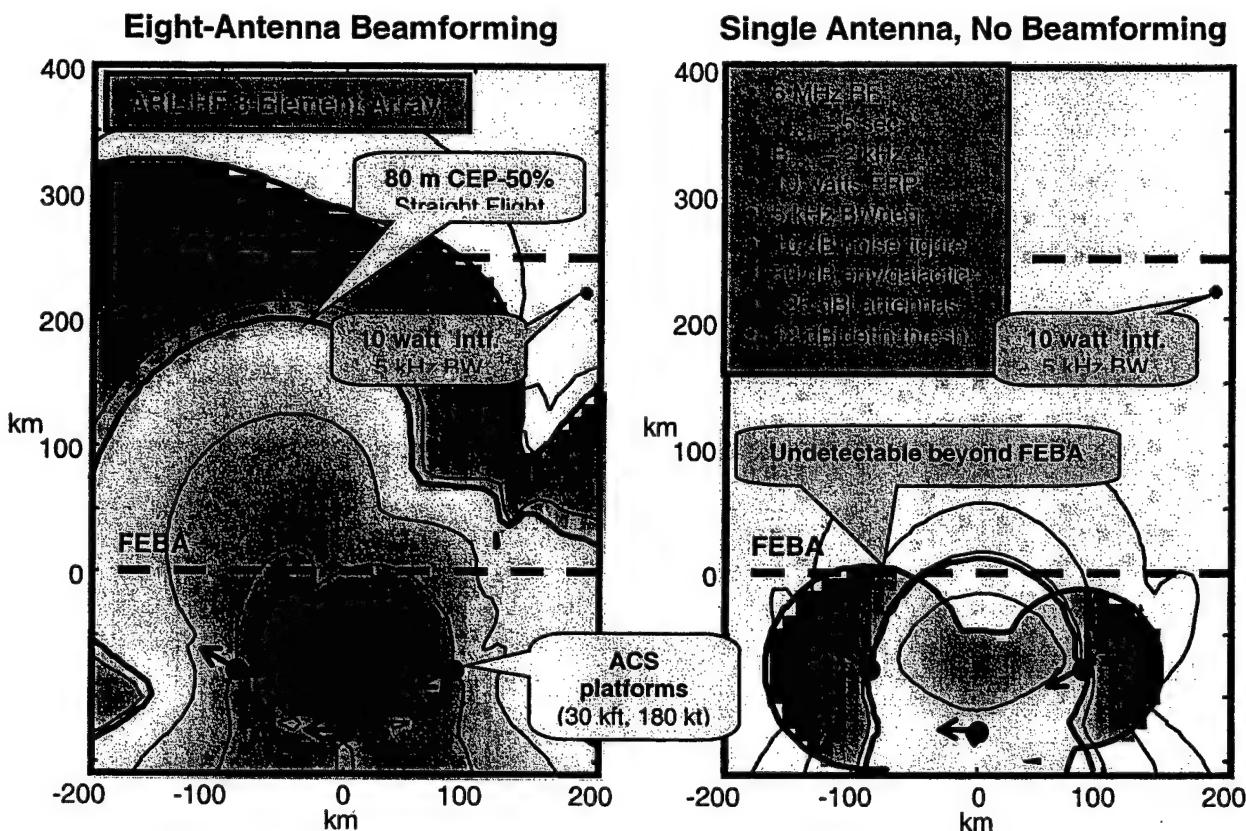

Figure 9. Conventional SSB-Voice at HF, With and Without Beamforming.

The beamformed case shows greatly improved detection footprint, covering nearly the entire battle area, due both to interference nulling and coherent beamforming gain. Geolocation accuracy is better than 50 meters over most of the echelon width of 210 km. Both target and interference are vertically polarized, so the individual platform detection footprints have deep nulls in the direction of the interferer, as evident from the detection contour as well as the ridges in the geolocation accuracy surface.

Without beamforming, the target signal is virtually undetectable beyond the FEBA. Single antenna geolocation accuracy is also dramatically curtailed, and is worse than 1 km over most of the echelon.

Another example HF scenario is shown in Figure 10, where the interferer is moved to front-center of the enemy echelon area. Because of the close proximity to the collection platforms, the non-beamformed detection footprints are very small. With beamforming, however, not only is detection visibility maintained across the battle area, but the broad angular extent presented by the collection platform geometry provides good visibility even in the close vicinity of the interferer. Geolocation accuracy is degraded from the previous case, but is still better than 300 meters over most of the echelon.
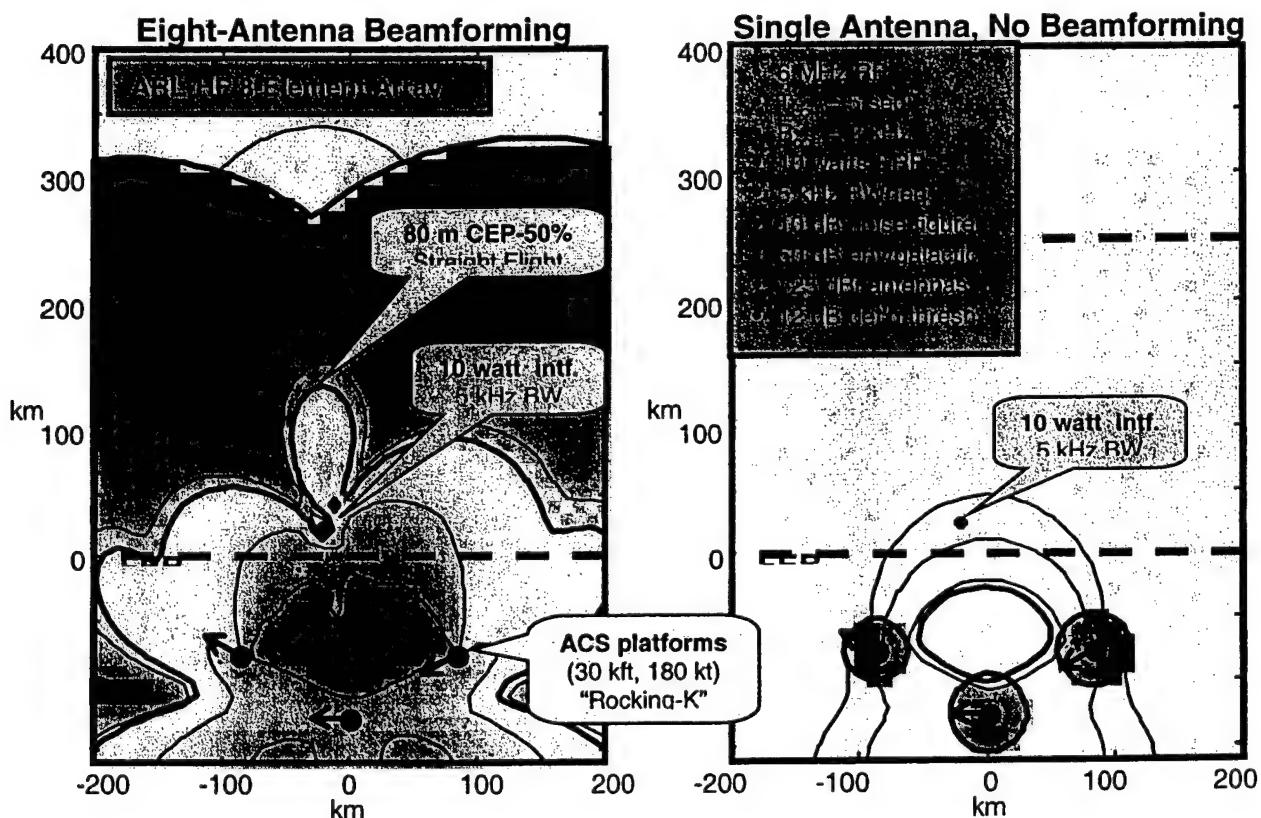

Figure 10. Conventional SSB-Voice at HF, Nearby Interferer.

6.   Beamforming Geolocation of LPI Signals.

The PinPoint approach to precision geoloction of LPI signals is based on coherently processing the LPI waveforms after detection and tracking of specific emitters. The noise bandwidth is therefore roughly matched to the LPI signal bandwidth rather than the full collection bandwidth. Accurate geolocations are obtained with relatively short collects, even with only fractional bandwidth RF coverage.

Even without co-channel processing, moderate-power VHF LPI emitter activity can be detected at moderate range since a small fraction of the detections are likely to appear in reasonably interference-free regions of the spectrum. However, co-channel processing greatly increases the probability of emitter identification and tracking, and quickly becomes absolutely necessary for good long-range performance against low-power LPI at VHF in dense signal and interference environments.

6.1   LPI Detection and Beamforming

Wideband beamforming of instantaneously narrowband LPI signals is achieved at the collection platform by implementing a bank of narrowband detection and beamforming channels. The DMP beamforming algorithm is ideally suited to this function, and forms the backbone of the LPI co-channel processing thread shown in Figure 11. The DMP algorithm detects the signals and determines copy weights, which are used for co-channel DF and beamforming. The pre-D beamformed waveform is analyzed for validation and relevant signal-external parameter estimation, and the signals are associated into emitter tracks.

The track data for an intercepted emitter and the corresponding beamformed Pre-D waveforms are downlinked to the PinPoint processor for precision geolocation. Data collected from separate platforms are readily associated via the track information, even with partial-band coverage as long as both platforms are tuned to the same band and a high percentage of the signals are intercepted by both platforms (another motivating factor for co-channel processing).

Interplatform-associated data are cross-correlated to form a coarse TDOA-DD measurement and geolocation. Bearing data can be averaged and triangulated to cue the coarse TDOA-DD geolocation search. The cross-correlation phases are then combined coherently across the intercept duration for precision geolocation. Platform motion, Doppler wavelength dependence, and delay drift effects are compensated for in the coherent integration by constructing phase-correlation sequences that are fixed in target geolocation coordinates and computed at each signal-up detection using current (smoothed) platform nav data.

ON-PLATFORM PROCESSING

SOI DETECT/COPY **UNTRACKED SOI**

ADC

PCN
Channelizer

IDMP-DMP
Det'n & DF

External Cues,
from other ptfms

External
Cue Filter

External Cues,
to other ptfms

Delay
Memory

BFN
Beamformer,
Fine Features

External Cue
data memory

Copy Pre-D,
from other ptfms

Paradigm-Aided
Beamform/DF

Copy Pre-D,
from other ptfms

Sort/Track

TOA/FOA/
AOA files;
Copy Pre-D

Reports,
Track info

External-Track
TOA/FOA/
φOA/AOA files

**GROUND-STATION
PROCESSING**

AOAs
(fine-DF)

Triangulate

TOAs

Coarse
TDOA/DD

FOAs

Fine
TDOA/DD

Copy Pre-D
(or φOAs)

Precision Geo

Figure 11. LPI Signal Prosecution: Detect, DF, Classify, and Geolocate.

When one platform intercepts an LPI emitter but other platforms do not, the intercepted pre-D waveform can be combined with pre-D data from the other platforms to make coarse TDOA-DD, correlation phase, and DF measurements provided the underlined SINR exceeds threshold after beamforming. The implementation may require low-latency cross-platform cuing and/or extended on-platform delay memories, and requires additional system engineering trades and possibly some additional front-end software and hardware.

6.2 LPI Geolocation Accuracy at VHF

The VHF interference environment is modeled as three horizontally polarized television stations with the same radiated power spectra as used for the VHF conventional emitter analyses. The functional CEP-50 analysis for LPI makes some additional approximations and assumptions in

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order to represent the partial intercepts obtained without beamforming with wideband LPI, as shown in Figure 12. The LPI coverage bandwidth is 5 MHz, entirely within the TV spectrum.

Without beamforming it is assumed that only 1 MHz of the spectrum is "clear," so the intercept duty factor is 1/5 and the interference to noise ratio is averaged over that 1 MHz. This assumption is reasonably valid at the long-range detection limit. As it turns out, geolocation accuracy is primarily dependent upon collect duration rather than bandwidth at coherent bandwidths of 1 MHz or more, so the only error incurred at closer ranges is due primarily to underestimation of the integrated SINR, and is not off by more than a factor of 2-3 dB or so.
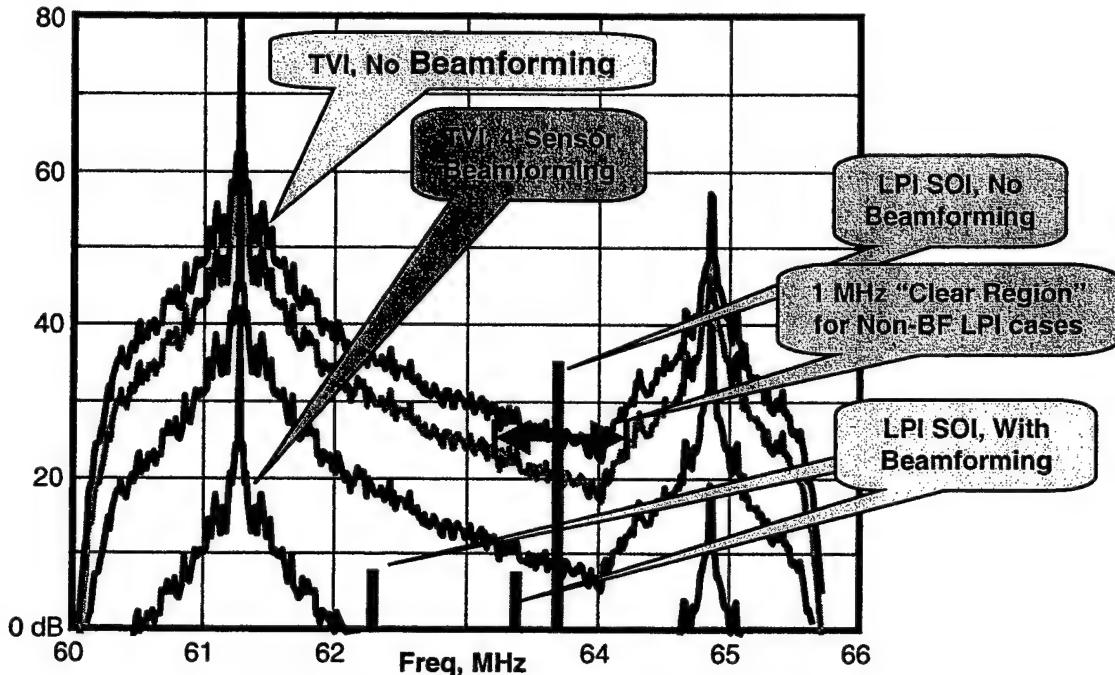

Figure 12. Television Interference Model, LPI Signals.

With beamforming, the intercept duty factor is assumed to be 100%, i.e. no additional TV residuals are modeled beyond the three televisions included in the scenario. The TV power is averaged over the 5 MHz spectrum for purposes of beamformer weights calculation, as if one beamformer covered the entire band. This assumption is perfectly reasonable for the purposes of computing beamformed gain on the SOI in the presence of the adapted nulls, since the array is not overloaded (the number of signals plus interferers is less than the number of antennas).

Geolocation accuracy is shown with and without beamforming in Figure 13, for a "Rocking-K" ACS formation against a low-power (1 watt) LPI emitter at roughly 60 MHz. The five-element beamforming array is the same as used for the conventional VHF analysis. With beamforming, the emitter is detected by at least one of the platforms to a depth of 200-250 km beyond the FEBA across the entire battle area. Furthermore, most of the near-FEBA area is covered simultaneously by all platforms (the grey contour of Figure 13) so most of the LPI emitter throughput is covered without special cross-platform cuing.

The geolocation accuracy with beamforming is better than 80 meters CEP over nearly the entire Corps echelon battle area. The dashed blue contour of the figure indicates the slight degradation in CEP from that of an ideal array, due to the wideband frequency response ripples that arise from nearfield-scattering effects, as measured from actual flight-test array calibration data for a fielded VHF airborne DF array. This response could potentially be calibrated out to some degree with the use of precisely modulated wideband calibration waveforms instead of the more traditional stepped-CW tones for the array calibration flights.

In contrast, without beamforming, the 1 watt LPI emitter is only detected in the very near zone of the enemy battle area, and even then, the area coverage is intermittent. The emitters of interest are only seen by one platform at a time if at all, so low-latency interplatform cross-cuing (or large delay memory, or wide downlink bandwidth) is required. Even with emitter paradigms, obtained either via co-channel processing or from stand-in platforms, the single-antenna geolocation accuracy is degraded to 300-1000 meters at the further reaches of the battle area.
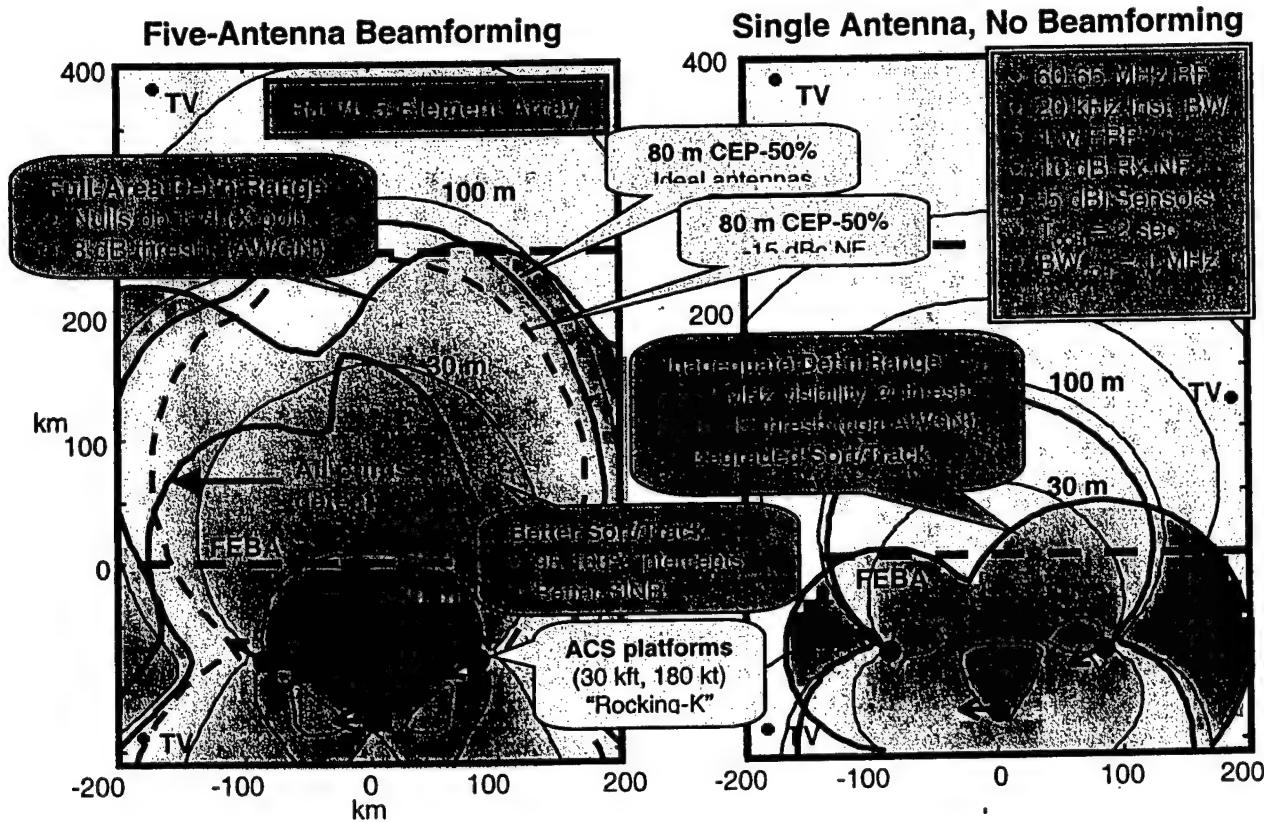

Figure 13. LPI Signal at VHF, With and Without Beamforming.

A stand-in TUAV scenario potentially representative of a Prophet-Air mission is shown in Figure 14. The beamforming antennas are again vertical blades of 1 meter in length, positioned at the ends of a 5' by 7' cross aligned with the wings and fuselage of the TUAV. These

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dimensions were picked after a cursory review of a Shadow 200 drawing, with the idea that the airframe might be sufficiently strong at those points (nose, tail, wing fuel tank areas) to support the antenna loading. The beamformed patterns for this array were computed at 60 MHz.

The collection bandwidth was 10 MHz step-scanned across 30-90 MHz for an average intercept duty factor of 1/6 in the beamformed case. For the non-beamformed case, an additional duty factor of 1/5 is assumed (for a total duty factor of 1/30) to account for the limited spectral visibility between television carriers. The television interference scenario was assumed to be the same across the entire LPI emission bandwidth. (Geolocation accuracy is independent of LPI bandwidth beyond 5 MHz or so due to other accuracy-limiting effects.)

With beamforming, the detection footprint of each TUAVcovers most of the division echelon battle area for the 1 watt emitter, supporting a geolocation accuracy better than 80 meters CEP without the need of special cross-platform cuing. The Corps echelon area is also covered by at least one platform, which opens the possibilities for interoperation with ACS, perhaps enabling instantaneous battle area mapping with only two ACS platforms.
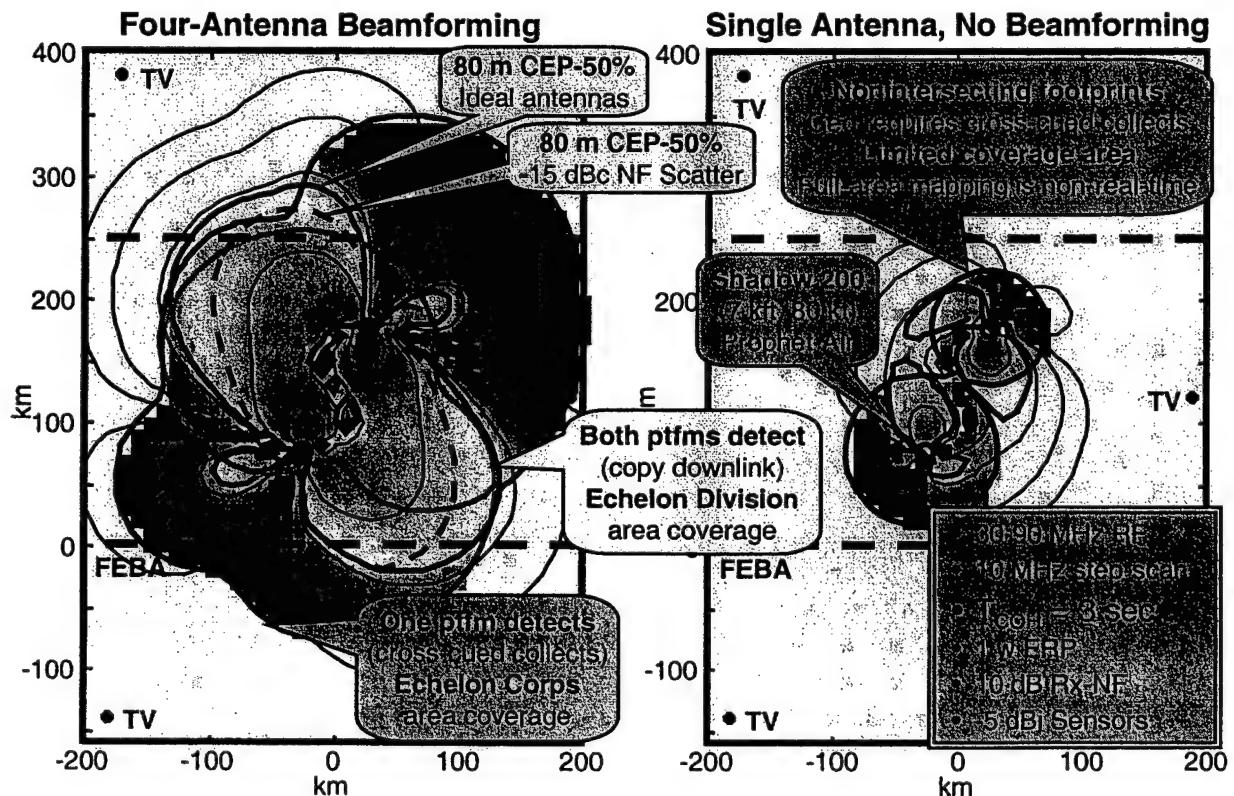

Figure 14. Step-Stare LPI Processing from Tactical UAV (Prophet Air).

Without beamforming, the TUAV detection footprints are small and nonintersecting in this flight formation shown. Even with platforms flown in closer formation, the footprint intersection will be small and the battlefield will have to be swept, for only periodic (non-real-time) mapping.

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6.3   SSB-Voice HF-LPI Geolocation-Aided Processing

SSB-Voice LPI emitters of the sort often used at HF can be difficult to process in a dense environment because the poor timing and angular resolution obtained on the individual signals makes the emitter identification, association and tracking problem ambiguous when multiple emitters transmit simultaneously. Multi-platform TDOA-DD processing of the individual emissions can be used as a powerful discrimination feature, greatly improving the LPI sort-track performance. After emitter association, the coarse TDOA-DD correlations can be integrated for a highly accurate precision geolocation.

An example of coarse and fine geolocation accuracies for an ACS collection scenario at HF (6 MHz) is shown in Figure 15. The LPI emitter bandwidth is 100 kHz with an instantaneous bandwidth of 2 kHz (commensurate with SSB-Voice) at 10 watts ERP. The interference consists of isotropic environmental and galactic noise representative of the midwestern United States, and a single wideband interferer of 2 watts/kHz radiated power spectral density. The antennas are the same as used for the conventional-signal HF analysis.
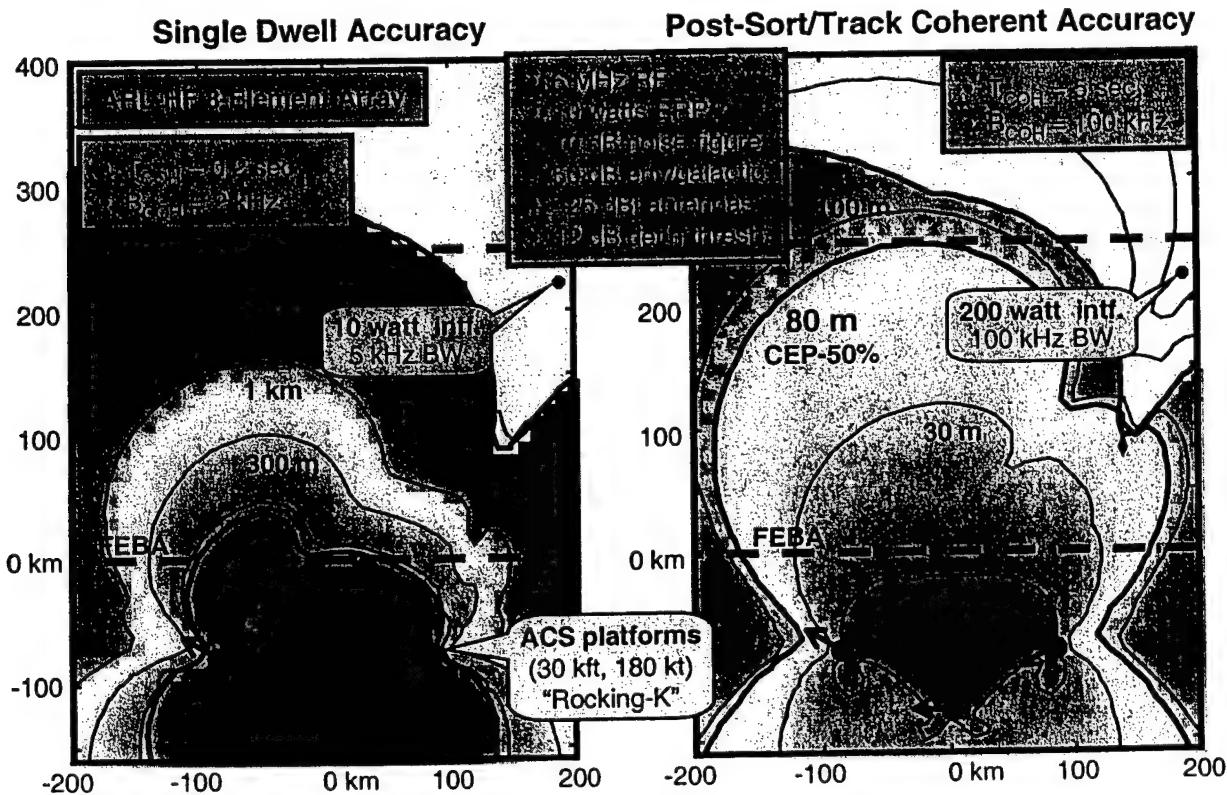

Figure 15. SSB-Voice LPI at HF: Coarse and Fine Geolocation Acuracy.

The geolocation of a single emission of duration as little as 0.2 seconds is already accurate to 50-100 meters in the signal-dense area near the FEBA, degrading to no worse than 3-10 km at the furthest reaches of the Corps echelon battle area. This level of accuracy supports the LPI sort-

track function unambiguously for nearly any conceivable engagement scenario. After emitter association, a 5 second collect supports geolocation accuracy of 80-100 meters at the far edges of the echelon, and 10-30 meters near the FEBA.

7. Beamforming Geolocation of Special Signals.

The baseline PinPoint geolocation processing approaches to tactical single-channel VHF emitters extend readily to most other signals of tactical interest as well. In particular, conventional signals of wider bandwidths can be treated in much the same manner as narrowband tactical signals, in terms of beamforming and geolocation. The primary differences in the signal prosecution thread are with regard to the signal detection and beamformer cuing functions.

7.1 Wideband Conventional Signals

Most of the wideband conventional signals of tactical interest have constant modulus or QAM modulations, and are readily beamformed with MT-CMA adaptation algorithms. Since these signals tend to be up for long periods of time, the detection cue generally comes from a periodic background environmental survey using the JML co-channel detection and DF algorithm.
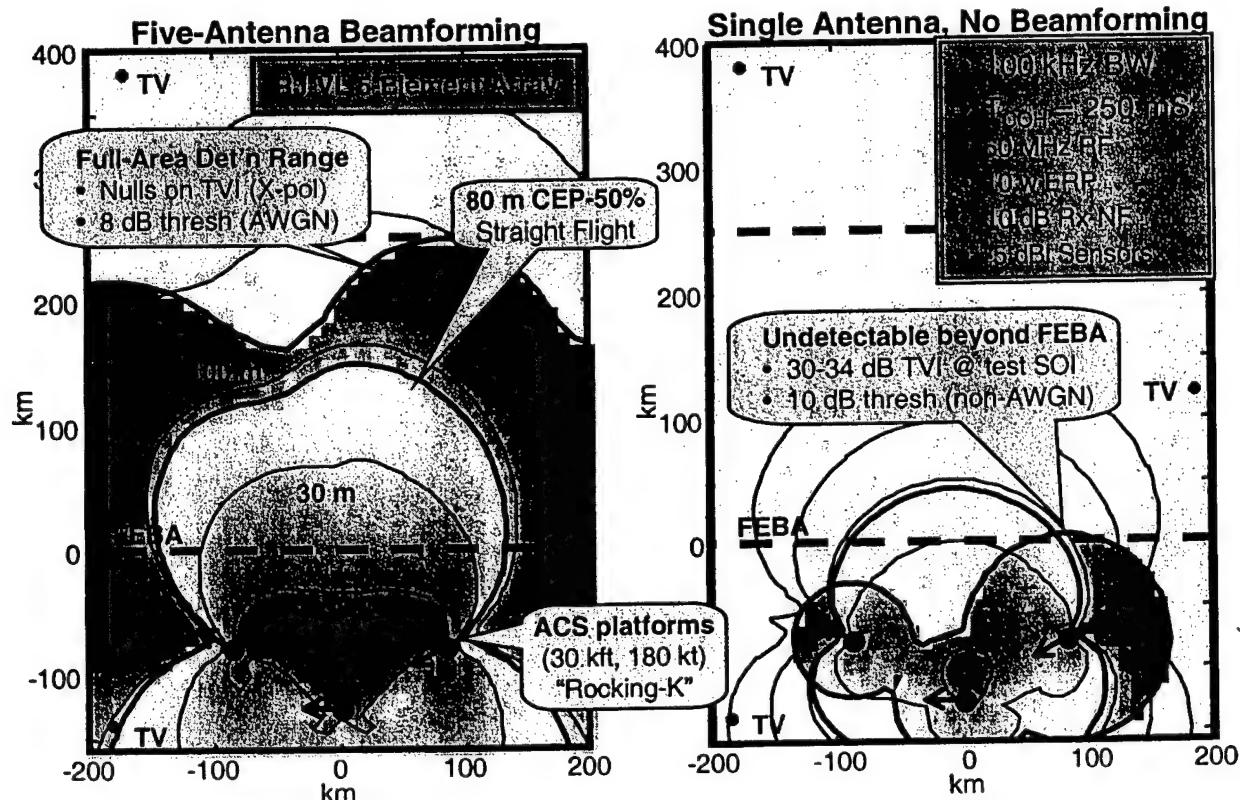

Figure 16. Wideband Conventional Signal at VHF, With and Without Beamforming.

An example of a VHF tactical wideband signal at 60 MHz and 10 watts is analyzed for geolocation accuracy with and without beamforming in Figure 16. The signal bandwidth is 100 kHz, and the collection interval has been reduced to 0.25 seconds to keep the link requirements

similar to the single-channel case. The detection footprint with beamforming extends 200-250 km beyond the FEBA, and supports geolocation accuracy of 20-30 meters near the FEBA and 100-300 meters at the far side. Without beamforming, the emitter is not detected beyond the FEBA, and with single antenna geolocation the accuracy is degraded by a factor of 3 near the FEBA, and 10 farther away.

The bandwidths of these signals can be as great as 500 kHz – 1 MHz. At the wider bandwidths, single-channel beamforming null depths are degraded due to channel imbalances in the receivers or even at the antennas themselves. Narrowband interferers use up one full nulling degree of freedom each even if the interferers are not cochannel amongst themselves, i.e. are tuned to different frequencies.

Receiver imbalances can be removed by pre-beamformer channel equalization, using filter weights computed from the receiver TDOA compensation data. Antenna response imbalances and narrowband interferers require space-time or space-frequency (poly-channel) adaptive beamforming techniques. These beamformers can be blind-steered in a manner similar to single-channel MT-CMA, but require additional algorithmic detail to prevent multiple ports from attracting the same signal but at different delays.

7.2 TDMA Networks

The baseline PinPoint approach to TDMA network geolocation is to employ MP-SCORE GeoSort beamforming to detect and locate the net members. The net is actually identified and its members associated after geolocation, based on analysis of the pre-D copy data obtained using the MP-SCORE beamforming weights. Timeslot and frame synchronization is obtained from the waveform envelopes of each individual emitter. Because net members are resolved via their correlation peaks in delay-Doppler, this approach works best for wider bandwidth, higher frame-rate nets.

Narrowband, lower frame-rate nets can be identified and associated based on DMP detection, DF, beamforming and geolocation of the individual timeslot bursts. The LPI co-channel detection and processing thread shown in Figure 11 can be modified to perform this function in a staring (tipoff-cued) or step-scan (search) mode, perhaps with some parameter modifications to reduce the background nulling memory.

TDMA-Net tipoff cues would be very useful for tasking the more computationally and resource intensive MP-SCORE and staring-DMP net-verification, identification, synchronization and geolocation algorithms. These cues can be generated from a scanning multi-antenna receiver such as the LBSS Rapid Spatial-Spectral Scan (RSSS) asset. Because of the relatively low revisit rate associated with wide spectral scanning coverage, most TDMA nets would generate tipoff "hits" mainly in response to changes in network traffic load, in particular on events such as a previously empty timeslot becoming active. The tipoff signature would be the occurrence of a series (or brief flurry) of singleton hits arriving from a single (or multiple discrete) angle(s) of arrival, over a relatively narrow frequency band. Similar events can be used for LPI tipoff, and in fact the response to either tipoff can be the assignment of an LPI signal processing thread to the frequency band, with additional report processing to recognize and classify TDMA net activity.

8. Conclusion and Recommendations.

Each of the Phase 0 objectives, as listed in Section 1.2, were met during the study, paving the way for actual development of the PinPoint Demonstration System under Phase 1, integration of the system with a multi-sensor beamforming and DF front-end (such as LBSS and/or the Army Testbed) under Phase 2, and flight testing under Phase 3. Specifically, the accomplishments under Phase 0 include:

- Algorithms were developed for combined beamforming and TDOA-DD processing, that are cued by signal-up detection at one or more platforms, for both conventional and LPI signals;

- Performance analyses were made via functional simulation for signal-up (cuing) detection footprint and geolocation accuracy, with and without beamforming, for tactical HF and VHF corps-echelon scenarios, for both stand-off (ACS) and stand-in (TUAV) flight geometries;

- Tactical HF conventional and LPI geolocation was addressed specifically, and geolocation-aided LPI tracking was shown to robustly solve the difficult HF SSB-LPI problem;

- Low-power tactical VHF single-channel push-to-talk emitters, both conventional and LPI, were shown to be robustly detectable and geolocatable with high precision in strong television interference across the corps-echelon battle area from safe standoff distances;

- Environment and platform dynamics effects were assessed for conventional signal (MT-CMA) beamformers in television and LPI interference with turning platforms by simulation;

- The compensation, calibration, timebase and navigation requirements to support PinPoint were assessed, and were found to be generally no greater than those required to support DF, beamforming and TDOA-DD functions individually;

- Platform motion compensation requirements and supporting techniques were defined and integrated directly into the geolocation calculations;

- The data link requirements to support PinPoint were defined; and

- The PinPoint Demonstration System requirements, hardware and software architecture were defined, culminating in an architecture definition for the Phase 1 PinPoint Demonstration System.

The essential conclusion drawn from the Phase 0 study is that adaptive beamforming is indeed readily integrated with precision TDOA-DD geolocation. Adaptive beamforming not only greatly increases detection range, enabling standoff coverage of the entire battlespace for even low-power handheld emitters in dense interference environments, but also greatly improves TDOA-DD geolocation accuracies over what could otherwise be achieved with single-antenna signal processing, using very manageable signal collection times.

This combination of technologies can be applied to yield a dramatic improvement in battlefield mapping capability, by enabling the precision geolocation of individual emissions with a high

probability of intercept. This capability in turn enables real-time situational awareness and battlefield mapping, and greatly enhanced emitter tracking and network analysis capabilities.

In general, at signal levels near the (co-channel) detection threshold, geolocation accuracies are similar to what would have been obtained via conventional single-antenna TDOA-DD processing in-the-clear, at the beamformed SINR. Similar accuracies can also be expected for wideband conventional and TDMA net signals.

Precision geolocations to within 80 meters (50% CEP) were shown to be achievable with typical ACS or Guardrail standoff collection geometries as well as Prophet-Air stand-in geometries against 1 watt tactical-VHF emitters (LPI or conventional) across nearly the entire battle area, in an interference environment with three high-power television stations around the battlefield periphery using arrays of only four or five antennas. Accuracies near the front line are considerably greater, ranging from just over 10 to 30 meters CEP. These accuracies require collection intervals of less than 2 or 3 seconds even with reduced-bandwidth collection of wideband LPI, enabling precision geolocation of each transmission.

PinPoint beamforming-TDOA-DD techniques can also be integrated with LPI emitter association and tracking techniques to form a powerful solution to the HF SSB-Voice LPI problem. Large numbers of such emitters can be robustly resolved and tracked, and high geolocation accuracy can be obtained from post-track integration from relatively short collects, enabling precision geolocation on individual transmissions.

In conclusion, we are highly encouraged by the results of the PinPoint Phase 0 feasibility study. We strongly recommend pursuing the PinPoint program through flight-testing as expediently as possible on the single-channel tactical VHF conventional and LPI radios, to validate and demonstrate the core PinPoint technology requirements. After successful flight tests, the program can then be expanded to extend the core technologies to other signal types of interest. We also highly recommend integrating the PinPoint and NRC technologies for a unified classify-geolocate capability in time for the first flight tests. These technologies address critical Army requirements and should be steered to directly support both the ACS and Prophet-Air DTUAV programs.

References

[1] Stein, S., "Algorithms for Ambiguity Function Processing," IEEE Trans. Accoust., Speech and Sig. Proc. Vol. ASSP-29, No. 3, June 1981.

[2] Chestnut, P., "On Combining Target Location Ellipses," IEEE Trans. Aerosp. and Elect. Systems, Vol. AES-25, No. 2, March 1989.

[3] Torrieri, D., "Statistical Theory of Passive Location Systems," IEEE Trans. Aerosp. and Elect. Systems, Vol. AES-20, No. 2, March 1984.

[4] CCIR Resolution No. 22, "International Telecommunications Union Atlas of Ground Wave Propagation Curves for Frequencies Between 30 and 10,000 Mcs." (Geneva)

[5] Norton, K., "The Propagation of Radio Waves Over the Surface of the Earth and In the Upper Atmosphere, Part I," Proc. Inst. Radio Engineers, Vol. 24, No. 10, October 1936.

[6] Norton, K., "The Propagation of Radio Waves Over the Surface of the Earth and In the Upper Atmosphere, Part II," Proc. Inst. Radio Engineers, Vol. 25, No. 9, September 1937.

[7] Barnes, J., et al., "Characterization of Frequency Stability," IEEE Trans. Instrumentation and Measurement, Vol. IM-20, No. 2, May 1971.

[8] Agee, B., "Blind Separation and Capture of Communications Signals Using a Multi-Target Constant Modulus Beamformer," 1989 IEEE Military Communications Conference.

[9] Agee, B., "Fast Acquisition of Burst and Transient Signals Using a Predictive Adaptive Beamformer," 1989 IEEE Military Communications Conference.

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